Asteroseismology of B stars with MESA

Anne Thoul
FNRS, ULg
Outline

What is MESA (and GYRE)?

Some examples of MESA results for B stars
with Pieter Degroote and «the best students» from the MESA summer school 2013

Asteroseismology of 15 CMa (very preliminary)
with Maryline Briquet and Sophie Saesen
What is **MESA**?

Modules for Experiments in Stellar Astrophysics

**MESA star: 1D stellar evolution code**

- Open Source
- Independent modules
- Up-to-date, flexible
- Constantly evolving to include latest macro- and microphysics
- Performance: use of parallelism, multi-core architectures
- Wide applications in stellar evolution

**Bill Paxton**

[mesa.sourceforge.net](http://mesa.sourceforge.net)
Well documented ➔ MESA instrument papers:


MESA Forum: mesastar.org

Mailing list: mesa-users

MESA SDK (Software Development Kit)

Rich Townsend
What can MESA do?

Everything a 1D stellar evolution code can do...

see instrument papers

MESA is constantly checked
• internally (consistency, accuracy, predictibility)
• externally:
  - compared with other codes (when possible)
  - compared to reproducible evidence
What can **MESA** do?

Flexible: Possible to access all the variables used during the evolution to perform extra computations (using `run_star_extras.f`)

Example from the MESA summer school 2013:
Verify that the MESA models are in hydrostatic equilibrium
(mesastar.org/documentation/mesa-summer-school-2013/asteroseismology-of-b-stars-with-mesa)

\[
\frac{dP(r)}{dr} = -\rho(r)g(r)
\]

\[
2 \frac{P_{i-1} - P_i}{dm_{i-1} + dm_i} = -\frac{Gm_i}{4\pi r_i^4}
\]

\[
q_i = \frac{|LHS_i - RHS_i|}{\max(|LHS_i|, |RHS_i|)}
\]

B star MS model

www.ster.kuleuven.be/~pieterd/mesa/
Using MESA

✔ Set up the INLIST
✔ Customize MESA
✔ Run MESA
Asteroseismology:

Use observed stellar pulsations properties (frequencies, mode identification, mode amplitudes,...) to gain insight about the stellar interior structure

Stellar evolution code

+ 

Stellar oscillation code
MESA profiles can be fed into pulsation codes such as ADIPLS

MESA is now coupled to GYRE

⇒ much simpler
GYRE
Stellar oscillation code
Rich Townsend

- Open Source
- Adiabatic and Non-adiabatic pulsations
- Efficient use of multi-cores architectures

bitbucket.org/rhdtownsend/gyre/wiki/home

Asteroseismology of Main Sequence B stars

\[ \log T_{\text{eff}} \sim 4.1 - 4.5 \]
\[ \log L/L_\odot \sim 2 - 4 \]
\[ M/M_\odot \sim 4 - 20 \]

Multiperiodic pulsators:
- low-order p, g, mixed modes (β Cephei)
  periods of a few hours
- high-order g modes (SPB)
  periods 0.5 - 5 days

Long-lived modes
κ mechanism in Fe opacity bump
⇔ cf. Coralie Neiner’s talk
Asteroseismology of Main Sequence B stars

pressure (or acoustic) waves: frequency related to sound speed

\[ \nu \propto \frac{c}{R} \propto \sqrt[3]{\frac{M}{R^3}} \propto \sqrt{\rho} \]

⇒ info about the mean density

gravity modes: frequency related to the BV (buoyancy) frequency

\[ N^2 = -\frac{g}{r} \left( \frac{1}{\Gamma_1} \frac{\ln p}{\ln r} - \frac{\ln \rho}{\ln r} \right) \approx \frac{\rho g^2}{p} (\nabla_{\text{ad}} - \nabla + \nabla_{\mu}) \]

⇒ info about T and \( \mu \) gradients at core boundary
Asteroseismology of Main Sequence B stars

B stars have a simple internal structure:
convective core + radiative envelope

Some of the remaining open questions:

Size of the convective core; influence of mixing
mixing mechanisms
internal differential rotation
excitation of the observed modes (low frequencies in hybrids)
B pulsators in LMC and SMC
Asteroseismology of Main Sequence B stars

Modularity of MESA

→ simple to test different physics ingredients

• different compositions
• different opacity tables
• different treatments of the convection
• different mixing mechanisms and/or prescriptions
• effects of the rotation (as modeled in this 1D code)
• ....
Asteroseismology of Main Sequence B stars

examples from MESA summer school 2013:
(see also mesastar.org)

Ex. 1: The $\beta$ Cephei Instability Strip
Ex. 2: High-order gravity modes period spacings in SPBs
Asteroseismology of Main Sequence B stars

Example: Probing the $\beta$ Cephei Instability Strip

Miglio et al. 2007

CLES

www.ster.kuleuven.be/~pieterd/mesa/

Results of the best student team during the 2013 MESA summer school
Asteroseismology of Main Sequence B stars

Example: High-order gravity modes period spacings
ΔP is uniform in the asymptotic limit ... but:

receding core:
→ \( \nabla \mu \) at core boundary
→ sharp feature in BV frequency
→ sinusoidal component in ΔP

Signature of evolutionary stage

Information about the mixing at core boundary

\[
\Delta P = P_{n,t} - P_{n-1,t} = \frac{2\pi^2}{\sqrt{l(l+1)}} \frac{1}{\int \frac{N(r)}{r} dr}
\]

Miglio et al.

CLEs

www.ster.kuleuven.be/~pieterd/mesa/
Asteroseismology of $\beta$ Cephei stars

Sparse spectrum of p modes

$\nu$ Eridani

HD129929

Ausseloos et al. 2004

Aerts et al. 2004

Fit individual modes $\Rightarrow$ age, $T_{\text{eff}}$, log $g$, Z, M, R, ov
Asteroseismology of \( \beta \) Cephei stars
Asteroseismology of the $\beta$ Cephei star 15 CMa

See talk by Sophie Saesen

\begin{align*}
  f_1 &= 5.1831 \text{ d}^{-1} & l &= 0 & m &= 0 \\
  f_2 &= 5.4187 \text{ d}^{-1} & l &= 1, 2, 3 & m &= 0 \\
  f_3 &= 5.3085 \text{ d}^{-1} & l &= 3, 4 & |m| &= 1 \text{ or } 2 \\
  f_4 &= 5.5212 \text{ d}^{-1} & l &= 1, 2, 3 & m &> 0
\end{align*}

Very preliminary modeling!
Asteroseismology of the β Cephei star 15 CMa

Stellar models: use MESA

The ingredients for the inlist:

- chemical composition
- network of nuclear reactions
- opacity table
- equation of state
- photosphere
- treatment of convection
- overshooting
- other mixing
- mass
- metallicity

AGS2009

OPAL

Diffusive overshooting

\[ f = 0 \text{ to } 0.016 \]


\[ M = 10 \text{ to } 13 \, M_\odot \]

\[ Z = 0.01 \text{ to } 0.02 \]
Asteroseismology of the β Cephei star 15 CMa

**Evolutionary tracks**
fit radial fundamental mode frequency ⇒ fix the age (evolutionary stage) of the star

![Graph showing evolutionary tracks](image)
Asteroseismology of the $\beta$ Cephei star 15 CMa

Results for all calculated models
fit radial mode frequency $\iff$ fix log $g$
Asteroseismology of the β Cephei star 15 CMa

Impossible to fit the second axisymmetric mode with l=1
Asteroseismology of the β Cephei star 15 CMa

$l=2$

$l=3$
Asteroseismology of the $\beta$ Cephei star 15 CMa

mode excitation
Asteroseismology of the $\beta$ Cephei star 15 CMa

Work in progress....!

WAITING FOR:

- progress in identification
- information on the rotation velocity

TO DO LIST:

- Improve modeling
- Look at the mode excitation
- Study the impact of composition and opacities
Thank you!